Scientific Objective 3: Radiative Models

The purpose of scientific objective 3 is to test and improve atmospheric models of radiation, radiatively active substances, and radiative effects.

Introduction

Scientific objective 3 encompasses two major research areas. The first is that of providing input data for models which describe radiative energy exchange in the Earth's atmosphere and the effects on this exchange of altered atmospheric composition. The second is that of providing input data for studies which test the basic assumptions used to analyze data from passive remote sensors. Here again, changes in atmospheric constituents (aerosol particles or thin cirrus, for example) may affect the values of the atmospheric parameters inferred from the data.

A major reason for the current interest in radiative energy exchange is that alterations in this exchange can in turn alter the climate. Within the past few years, public concern for problems associated with climatic fluctuations has increased dramatically. The impact of climate variability has been vividly demonstrated by the effects of record cold winters on energy demands; the loss of life and property caused by record snowfalls, extreme flood events, mudflows, and landslides; and the effect on food and water supplies of droughts in England, the U.S.S.R., Africa, and the Western United States. We are also aware that man's activities, in part by altering atmospheric composition and surface albedo, have already affected local and regional climates and may affect the global climate as well.

A growing concensus and sense of urgency concerning the Nation's needs for understanding and anticipating climatic changes has led to the development of A United States Climate Program Plan (1977) by the Interdepartmental Committee for the Atmospheric Sciences, which calls for the development and coordination of needed climate research and services by the Federal Government. In response to this call, the NASA Goddard Space Flight Center developed a Proposed NASA Contribution to the Climate Program in 1977, which shows how our practical understanding of the behavior of the climate system could be advanced by concerted use of space-based global observations and by application of NASA's data management, analysis, and coordination capabilities. Shuttle lidar could play an important role in this process by providing unique data on atmospheric constituents and surface properties that affect the radiation budget, while coordinated measurements could document the radiative quantities per se. (See examples in the section "Earth Radiation Budget Studies.")

In parallel with the current interest in radiative effects on climate, there is an ongoing interest in the effects of minor atmospheric constituents on passive remote sensors. This interest derives from the major and growing role that these passive sensors play in a variety of applications. For example, data from passive, nadir-viewing temperature sounders are routinely used in operational weather forecasts, and the impact of these data is expected to increase as more and better sounders are flown. (See scientific objective 4.) Also, current and future limb-emission radiometers are expected to provide data

on minor constituents (e.g., O_3, H_2O, NO_x, and CFM's) that are vital to our understanding of the ozone depletion threat and other fundamental problems. (See scientific objective 2.) The outputs of both these types of radiometers can be affected by emissions from aerosol and cloud particles within the field of view. These effects, if significant, must be properly accounted for in reducing the radiometric data. However, this has been very difficult in the past because of the highly variable nature of aerosol and cloud particles, and the attendant difficulty in determining the presence, height, and effects of particles in specific data sets. Here again, data from a Shuttle borne or free-flying lidar, obtained with simultaneous data from the passive sensors, could provide unique advances in resolving some of these important questions. (See section entitled "Effects on Passive Sensors.")

Table I summarizes the measurements needed to provide significant advances in verifying radiative models for both the climatic and remote-sensing applications. The table lists the required accuracies and resolutions and relates these needs to specific lidar experiments and correlative sensor types. One parameter in table I that requires special mention is $\sigma_v(\lambda)$. This parameter is used to identify the collective effects of aerosol or cloud particles on the transfer of solar and terrestrial radiation as required in a particular study. Thus, $\sigma_v(\lambda)$ could represent the spatial distribution of extinction or absorption cross section as a function of wavelength λ, or the scattering cross section as a function of scattering angle (i.e., the phase function), or a combination of these. (None of these cross sections is measured directly by lidar, but with careful use of conversion factors, lidar can often provide the best remotely sensed data available; we will return to this point below.) To characterize the radiation field sufficiently, the models also require information on gaseous constituents for the same location as the aerosol and cloud data. These important gases are also listed in table I. In each case, accuracies and vertical resolutions are varied with altitude in a manner that reflects the importance of the contribution of each constituent to variations in the total radiation field. Temperature profiles are also required, both as inputs to infrared radiative calculations and to verify the heating profiles that the calculations yield. It does not appear necessary to specify profiles of CO_2 directly since temperature data and the common assumption that the CO_2 mixing ratio is constant above the boundary layer can be used to calculate a sufficiently accurate CO_2 concentration profile.

The final entries in table I reflect the need of radiative climate models for data on the albedo of the Earth's surface or the albedo of the Earth's atmosphere underlying a height of interest. Proper treatment of information on clouds, such as the fractional cloud cover, cloud heights, and the presence of thin cirrus layers, is also very important in both the radiative climate models and the analysis of passive sounding data.

With reference to the parameter $\sigma_v(\lambda)$, it was mentioned above that lidar does not directly measure the particulate extinction, absorption, and angular scattering coefficients required by the radiative models. While this is strictly true, it is also true that occasional, carefully designed correlative studies using in situ or passive remote sensors in conjunction with ground-, air-, or space-based lidar can yield reliable factors for converting lidar-measured backscattering to certain of the desired quantities. This procedure

has already been used with good success in the case of the stratospheric aerosol (e.g., Northam et al., 1974; Russell et al., 1976). These correlative studies yield optical models on which the conversion factors are based. For a given subsequent lidar observation, the optical model is never certain, but it can often be sufficiently bounded (by using multiwavelength lidar data, expected variabilities from intermittent correlative measurements, information on the source, height, and temperature of observed particles, etc.) so that conversion uncertainties are understood and are minimized. When such carefully bounded conversion factors are combined with the unique spatial resolution and high sensitivity of lidar, the resulting description of particulate radiative parameters is usually more accurate than can be obtained by any other downward-looking remote-sensing technique (as must be used for global coverage of the troposphere). This is especially so because aerosol and cloud concentrations can be highly variable in space and time and are often confined to narrow layers. Thus in many cases, lidar-derived particulate radiative parameters do not need to be highly accurate to represent a significant and useful improvement over what is otherwise available. Examples of such cases include tenuous (often subvisible) cirrus clouds and Saharan, Mongolian, or urban haze layers.

In the following sections, we present more specific examples of important studies in which a Shuttle borne lidar could provide important data not attainable by other means.

Earth Radiation Budget Studies

Because of the widespread concern regarding possible climate change, many investigators (e.g., Charlson and Pilat, 1969; Atwater, 1970; Ensor et al., 1971; Rasool and Schneider, 1971; Mitchell, 1971; Barrett, 1971; Neumann and Cohen, 1972; Yamamoto and Tanaka, 1972; Braslau and Dave, 1973a and 1973b; Chýlek and Coakley, 1974; Shettle and Green, 1974; Harshvardhan and Cess, 1976; Coakley and Grams, 1976; Luther, 1976; Pollack, et al., 1976; Fiocco et al., 1976 and 1977) have developed models to assess the possibilities quantitatively. These models describe the radiative energy exchange in the Earth atmosphere system and what might be the effects on this exchange of changing aerosol, cloud, and trace-gas amounts, as well as changing surface albedos.

The well-documented effects of the injection of volcanic dust into the Earth's stratosphere by the Mt. Agung eruption of 1963 (see scientific objective 1) can be used to test a number of the climate theories. Following the eruption, anomalous increases in the stratospheric temperature were attributed to the presence of volcanic dust (e.g., Newell, 1971). One figure from Newell's paper is reproduced here as figure 1. It shows the difference in stratospheric temperature between January 1963 and January 1964 as a function of geographical location at an altitude of about 19 km. A large temperature increase is evident in the latitude strip between 0° and 20°S, with maximums around central Africa and New Guinea and over South America. Mugnai, et al. (1978) calculated stratospheric heating rates induced by aerosol particles at the 19 km level using data on the mean winter-time values of the planetary albedo as a function of latitude and longitude obtained from satellite observations (Vonder Haar and Ellis, 1974), the concentration and composition of

aerosol particles at the 19 km level predicted by a two-dimensional model of global-scale dispersion of the volcanic debris (Cadle et al., 1976), and data on temperature and concentration profiles for O_3, CO_2, and H_2O from the U.S. Standard Atmosphere Supplements, 1966. The results are shown in figure 2. A very high degree of correlation between the temperature differences in figure 1 and the heating rates in figure 2 is evident. Maximum heating rates of about 0.4 K per day are associated with temperature differences of about 8 K, thereby suggesting radiative relaxation time constants on the order of 20 days at the 19 km level.

In another test of the climatic perturbation of the Mt. Agung volcano, Hansen et al. (1978) computed the vertical temperature profile at low latitudes using a one-dimensional radiative-convective model. Their results, computed as a function of time before and after the eruption, also show good agreement with observations. Results for the stratosphere and the troposphere are shown in figures 3 and 4, respectively.

Although these models have provided many valuable new insights, a persistent lack of suitable global input data and of model verification has prevented predictions of future radiative-climatic conditions. In part because of this situation, a major parallel effort has been mounted to monitor the radiation budget directly on a global scale. Satellite-borne radiometers, such as the Earth Radiation Budget (ERB) sensors on Nimbus 6 and Nimbus 7, provide a powerful means of doing this. More complete data will be provided in the future by the multisatellite Earth Radiation Budget Satellite System (ERBSS). (See, e.g., Woerner and Cooper, 1977; Woerner, 1978.) Whereas the data from these sensors will by themselves be very instructive, they will be most beneficial when used with the radiation models mentioned above, and with simultaneous data on the radiatively important atmospheric constituents and surface properties. Coordinated studies of this sort can provide well-constrained checks of the mutual consistency of atmospheric constituent measurements, radiative calculations, and measured radiative effects. It is in this way that the most rapid progress will be made toward a reliable capability to predict future changes in Earth radiation balance and climate resulting from natural and manmade factors. For example, much could be learned from measuring and modeling the change in the Earth atmosphere albedo along a track passing from the South Atlantic, through the region of the Atlantic Saharan dust layer (see scientific objective 1), and into the North Atlantic, with the model constrained by simultaneously measured input data on the aerosol heights and densities and the surface reflectivity.

An attractive means of obtaining these coordinated data sets is by flying, along with ERB sensors, other sensors that measure the important atmospheric constituents and surface properties in the same region as viewed by the ERB sensors, and at the same time. Unfortunately, passive nadir-viewing sensors cannot provide aerosol and gas data with the required vertical resolution and accuracy, nor can they unambiguously separate surface from atmospheric effects; moreover, passive limb-scanning sensors are largely limited to the stratosphere and above, and cannot view the ERB sensed area simultaneously with ERB. These shortcomings are critical since the bulk of many radiatively important constituents (e.g., aerosols, tenuous clouds, and water vapor) is usually confined to thin layers in the troposphere, and rapid changes in these constituents often

provide the most instructive and least ambiguous tests of radiative models (e.g., Russell et al., 1979).

The lidar data could include aerosol and cloud particle backscattering coefficients and H_2O, O_3, and other gas concentrations, all with a vertical resolution equal to or better than that specified in table I. Also, total gas density profiles, or temperature profiles (using a more advanced lidar), could be measured and used to specify the CO_2 vertical profile. Surface reflectivity could be simultaneously monitored, and this, coupled with suitable models and "ground-truth" measurements, could provide a useful input on surface albedo to the radiative calculations.

Another lidar-measured parameter of value to the radiative calculations is the top height of opaque clouds within the ERB FOV. As noted in table I, variations in the height by as little as 0.1 km can be important in determining radiative fields and equilibrium temperatures; this is an accuracy that cannot be provided by passive sensors but can be achieved by lidar.

The unique ability of lidar to detect subvisible cirrus clouds is also worthy of mention. Previous ground-based and airborne lidar studies have detected tenuous cirrus clouds with water (ice) contents that were at least two orders of magnitude less than those associated with visible cirrus layers. Repeated lidar measurements in many latitudes have suggested that these subvisible cirrus layers are quite prevalent, but the lidar measurements to date have been too sporadic to provide a useful global or regional census. Also, these tenuous cirrus layers cannot be globally monitored by satellite multispectral radiometers since they are difficult to resolve unambiguously against complex backgrounds and are not discernible in the visible spectral ranges. Such tenuous clouds could produce measurable effects in certain ERB channels and, if widespread and persistent, could significantly perturb the global radiation budget. Only a space-borne lidar, co-aligned with an ERB sensor, could determine whether subvisible cirrus clouds were present in the ERB FOV during times of measured albedo changes. Such a space-borne lidar could also provide the first global census of the occurrence, height, density, and thickness of these tenuous clouds.

Effects on Passive Sensors

Both visible and subvisible clouds can influence the retrieval of temperature profiles from nadir-viewing multispectral infrared radiance measurements (e.g., Smith et al., 1972; Chahine, 1974). Procedures for adjusting for the influence of visible clouds have been developed, but they require an appropriately scaled specification of the height and amount of the clouds. Uncertainties in passively inferred cloud heights can thus introduce error into these procedures. Simulations by Halem and Chow (1976) indicate that the profile errors become significant for errors in the heights of high clouds with coverage of more than 50 percent. Although these simulations cannot be considered definitive because of persistent uncertainties in their treatment of cloud radiative properties, they nonetheless point to the need for improved cloud measurements, both as a check on the simulations and as an aid in developing improved analysis methods. A Shuttle borne lidar, co-aligned with a

temperature-sounding radiometer so that the fields of view of the radiometer and lidar are coincident, could provide the height information on visibl. clouds for this purpose, as well as height, thickness, and density information on subvisible clouds; these latter clouds are not accounted for in current data-reduction schemes (as their presence is not detectable), but their emissivities may make them significant contributors to the measured radiances and hence a significant source of error.

Dave (1978) has reported the results of an investigation aimed at estimating the effect of stratospheric and tropospheric particulate pollutants on total ozone measurements obtained from the Backscatter Ultraviolet (BUV) spectrometer aboard the Nimbus 4 satellite. His study showed that the total ozone in an atmospheric column could be in error by about ±2 percent due to particulate contamination encountered in the terrestrial atmosphere under average conditions and that the error could be expected to rise to about ±8 percent under strong particulate contamination conditions. A Shuttle borne lidar, co-aligned with a BUV instrument, could be used to test these predictions by obtaining simultaneous data on the vertical distribution of aerosol particles and ozone.

A variety of other experiments could also be performed to test other possible effects of aerosol particles on the passive sensors used to infer concentrations of various molecular constituents. Limb-scanning radiometers that infer stratospheric and mesospheric constituent profiles from measured infrared emissions can also be influenced by subvisible aerosol layers. For example, the Limb Radiance Inversion Radiometer (LRIR) on Nimbus 6 and the Limb Infrared Monitor of the Stratosphere (LIMS) on Nimbus 7 both determine ozone profiles by observing the infrared radiation emitted in the spectral interval from about 9 to 10 μm. Although the composition of the stratospheric aerosol layer is still quite uncertain, a number of investigators (e.g., Rosen, 1971; Toon and Pollack, 1973; Russell et al., 1976) have suggested that the stratospheric particles are a 75 percent by weight mixture of sulfuric acid in water. Figure 5 (from Mugnai et al., 1978) shows absorption cross sections for the 75-percent sulfuric-acid mixture that may be large enough to affect the 9 to 10 μm radiation detected by the limb-scanning radiometers for strong aerosol loading in the stratosphere - such as after the Mt. Agung and Fuego volcanic eruptions. Future detailed studies of this problem, and other similar problems involving the effects of infrared aerosol absorption or emission on concentrations of minor species detected by satellite sensors, may suggest additional Shuttle borne lidar experiments for testing and improving our techniques for obtaining data on atmospheric constituents.

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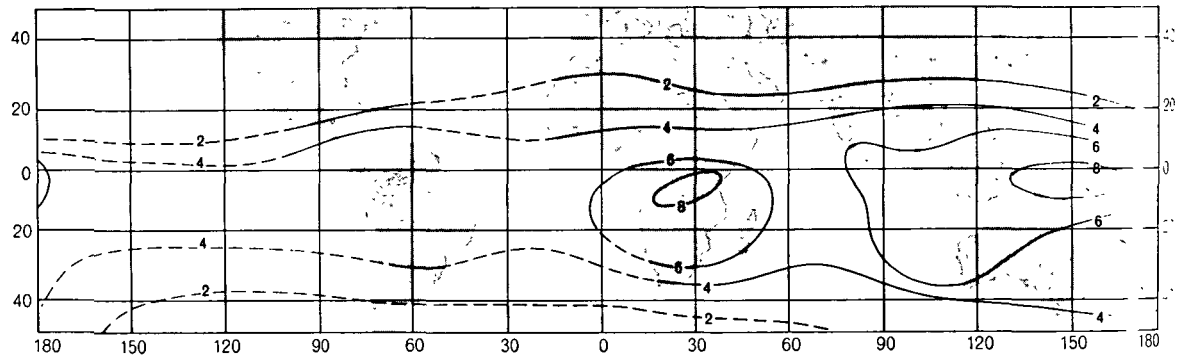
TABLE I.- SUMMARY OF MEASUREMENTS TO VERIFY RADIATIVE MODELS

Parameter	Height range, km	Δx, km	Δz, km	Remarks	Correlative sensors	Lidar experiment
$\sigma_v(\lambda)$[a]	0 to tropopause	100	0.5 to 1	10 percent to factor 3; haze, clouds, dust layers, thin cirrus	ERB sensor[c]; temperature and H_2O sounders[d]	1, 2, 3
	Tropopause to 100	200	2 to 4	10 percent to factor 5; stratospheric aerosols, mesospheric aerosols, noctilucent clouds	ERB sensor[c]; temperature and H_2O sounders[d]	4, 6, 24
H_2O	0 to tropopause Tropopause to 30	500 500	2 3	20 percent 50 percent to factor 2	ERB sensor[c]; temperature and H_2O sounders[d]	9, 10, 18
O_3	0 to tropopause Tropopause to 50	500 500	3 3	20 percent (5 percent of total O_3) 10 percent	ERB sensor[c]; BUV sensor[d]	10, 18 10, 12
CO_2	----------	----	--------	10 percent below 50 km; can be obtained from T(z)	ERB sensor[c]; temperature and H_2O sounders[d]	
CO_2 mixing ratios	70 to 100	1000	5	20 percent needed for input on radiative transfer for non-noctilucent conditions		13
Minor species (e.g., CFM's)	0 to tropopause Tropopause to 50	500 500	2 3	20 percent 20 percent		10, 18
Temperature	0 to tropopause Tropopause to 30 30 to 100	500 500 1000	2 3 3	1 K 2 K 5 K		17 17 17
Albedo	Surface	500	--------	0.01	ERB sensor	2
Cloud-top heights	0 to tropopause	[b]500	0.1		ERB sensor[c]; cloud-height radiometer	1

[a]Particulate scattering and extinction cross sections, as function of wavelength (or angle for scattering).
[b]Averaged quantity.
[c]For Earth Radiation Budget studies.
[d]For effects on passive sensors.



HEATING EFFECT after Mount Agung is mapped. The isotherms give the increase in mean temperature at about 19 kilometers, in degrees Celsius, from January before the eruption to one year later. (Broken lines indicate uncertainty due to scarcity of observations.)

Figure 1.- Increase in temperature at 19 km altitude from January 1963 to January 1964. (From Newell, 1971: The Global Circulation of Atmospheric Pollutants. Copyright © 1970 by Scientific American, Inc. All rights reserved)

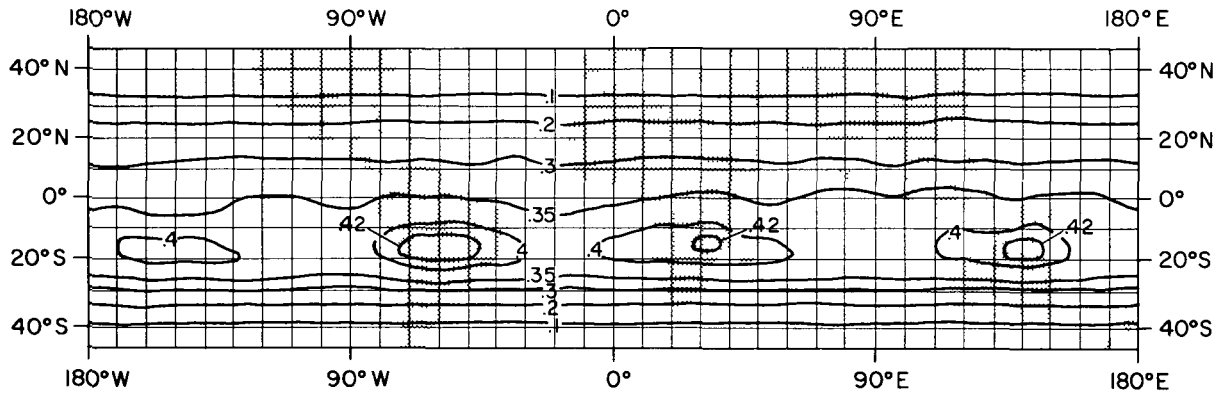


Figure 2.- Daily average heating rates (in K per day) at 19 km altitude for fine ash and impure sulfuric acid droplets 300 days following Mt. Agung eruption. (From Fiocco et al., 1977)

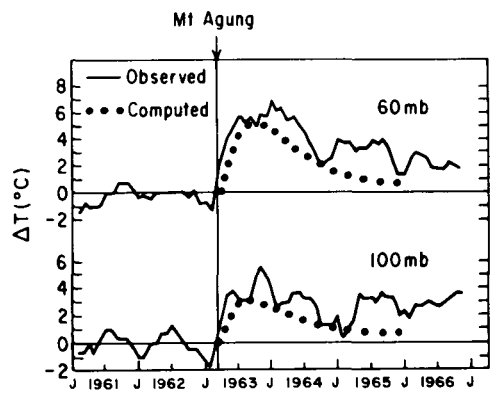


Figure 3.- Comparison between stratospheric temperatures before and after eruption of Mt. Agung as observed over Australia and as computed using a radiative-convective climate model. (From Hansen et al., 1978)

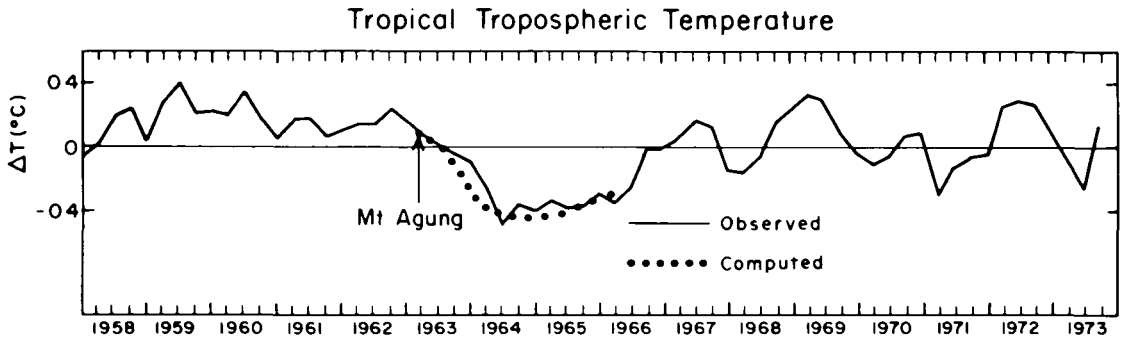


Figure 4.- Comparison between tropospheric temperatures before and after eruption of Mt. Agung as observed between 30°N and 30°S and as computed using a radiative-convective model. (From Hansen et al., 1978)

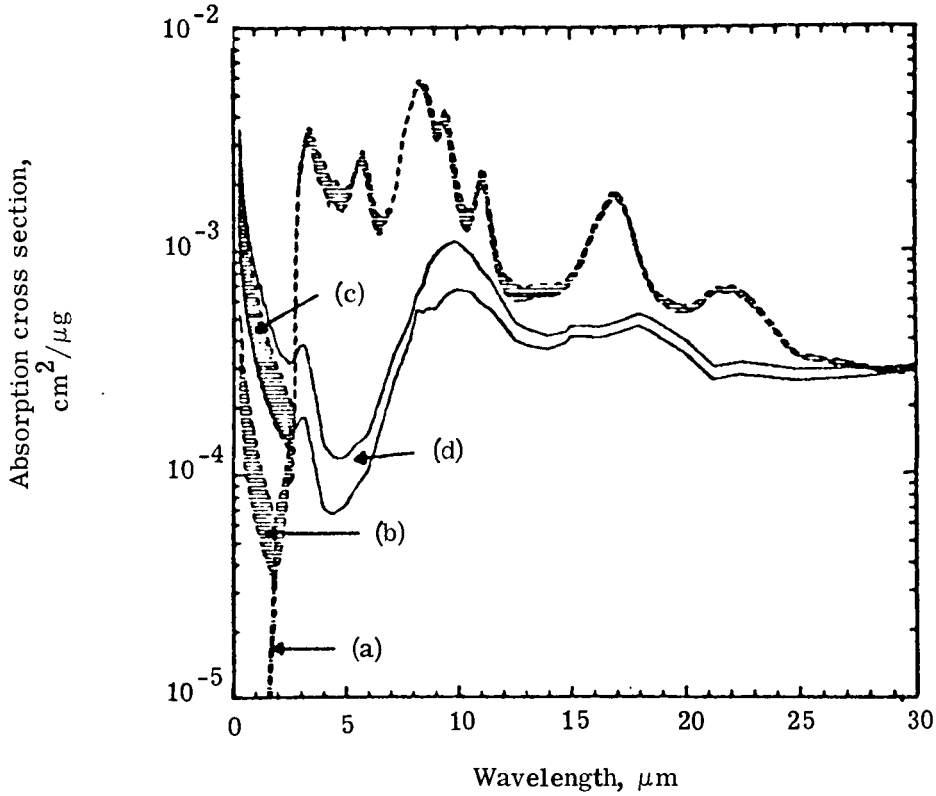


Figure 5.- Spectral variation of aerosol absorption cross section per unit mass for three models of a 75 percent by weight mixture of sulfuric acid and water (labeled (a), (b), and (c)) and for a volcanic ash model (labeled (d)). Each set of curves represents upper and lower bounds on cross sections for all particle radii between 0.01 and 1 μm. (From Mugnai et al., 1978, courtesy Royal Meteorological Society)